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Health and Climate Impacts of Scaling Adoption of Liquefied Petroleum Gas (LPG) for Clean Household Cooking in Cameroon: A Modeling Study

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Background: The Cameroon government has set a target that, by 2030, 58% of the population will be using Liquefied Petroleum Gas (LPG) as a cooking fuel, in comparison with less than 20% in 2014. The National LPG Master Plan (Master Plan) was developed for scaling up the LPG sector to achieve this target.

Objectives: This study aimed to estimate the potential impacts of this planned LPG expansion (the Master Plan) on population health and climate change mitigation, assuming primary, sustained use of LPG for daily cooking.

Methods: We applied existing and developed new mathematical models to calculate the health and climate impacts of expanding LPG primary adoption for household cooking in Cameroon over two periods: *a*) short-term (2017–2030): Comparing the Master Plan 58% target with a counterfactual LPG adoption of 32% in 2030, in line with current trends; and *b*) long-term (2031–2100, climate modeling only), assuming Cameroon will become a mature and saturated LPG market by 2100 (73% adoption, based on Latin American countries). We compared this with a counterfactual adoption of 41% by 2100, in line with current trends.

Results: By 2030, successful implementation of the Master Plan was estimated to avert about 28,000 (minimum = 22,000, maximum = 35,000) deaths and 770,000 (minimum = 580,000 maximum = 1 million) disability-adjusted life years. For the same period, we estimated reductions in pollutant emissions of more than a third in comparison with the counterfactual, leading to a global cooling of −0.1 milli °C in 2030. For 2100, a cooling impact from the Master Plan leading to market saturation (73%) was estimated to be −0.70 milli °C in comparison with to the counterfactual, with a range of −0.64 to −0.93 milli °C based on different fractions of nonrenewable biomass.

Discussion: Successful implementation of the Master Plan could have significant positive impacts on population health in Cameroon with no adverse impacts on climate. https://doi.org/10.1289/EHP4899

Introduction

Household air pollution (HAP) is a major risk factor for disease and disability in low- and middle-income countries (LMICs) (Gakidou et al. 2017). HAP is caused by incomplete combustion of solid fuels and kerosene in inefficient stoves and devices, which are used for household energy, including cooking, lighting, and heating (Bruce et al. 2013). Globally, approximately 2.8 billion people were exposed to HAP-derived harmful pollutants, and 2.6–3.8 million deaths were attributed to it, in 2016 (HEI 2018; WHO 2018).

The use of solid fuels for household energy needs poses risks to health and the environment and contributes to holding back economic development. These risks include *a*) death and illness from respiratory conditions and cardiovascular disease due to high levels of smoke inhalation (Smith et al. 2014), *b*) environmental harm from deforestation and air pollution (Sovacool 2012; Van der Plas and Abdel-Hamid 2005), and *c*) adverse impacts on society from suboptimal health, leading to reduced quality of life and a less economically active population (WB and IHME 2016). Reliance on solid fuel also has a detrimental effect on individuals and households from time lost resulting from gathering fuel and through inefficient cooking (Putti et al. 2015).

Sub-Saharan Africa has disproportionately borne the burden of HAP-related illness (Gakidou et al. 2017). In Cameroon, more than 70% of the population primarily cooks with biomass fuels, mostly fuelwood (more than 90% in rural regions) (INS and ICF International 2012). Exposure to particulate matter (PM) from all sources of air pollution was estimated to result in approximately 15,000 deaths and some 650,000 disability-adjusted life years (DALYs) lost in 2016 alone (IHME 2018).

A major driver for energy policy in Cameroon has been concerns about the degradation of forests from the gathering of fuelwood in addition to other causes. From 2001 to 2016, almost 900,000 hectares of forest have been lost in the country (WRI 2018), a 2.8% absolute decrease in forest coverage that translates to 114 megatons of CO_2 emission. Over the same period, the rate of deforestation has been quadrupled (WRI 2018).

Switching to clean cooking fuels such as liquefied petroleum gas (LPG) has the potential to deliver extensive health, social, and environmental benefits, including positively affecting climate in the short-term (Bruce et al. 2017; Rosenthal et al. 2018; Singh et al. 2017). LPG is a Tier 4 technology (the highest tier rating for clean cooking) under the International Organization for Standardization, International Workshop Agreement 11 (ISO/IWA-11) (Shen et al. 2018).

The International Energy Agency (IEA) includes LPG as a key fuel recommended to tackle energy-related air pollution emissions and proposes it as a solution for half of the 2.8 billion people still needing access to clean cooking fuels and technologies (IEA 2017). In addition, rapid scale-up of access to clean household fuels, such as LPG, was a key recommendation in published World Health Organization (WHO) Indoor Air Quality Guidelines on household fuel combustion (WHO 2014).

As part of its commitment to become an emerging economy by 2035—and to address the negative impacts on environment, deforestation, and energy security from solid fuel reliance—the Cameroon

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government has set a target that, by 2030, 58% of the population will be using LPG as a cooking fuel (in comparison with less than 20% in 2014) (Bruce et al. 2018; GLPGP 2019). In 2015, an interministerial, multistakeholder national LPG ad hoc committee, cochaired by the Global LPG Partnership (GLPGP), oversaw the development of a National LPG Master Plan (Master Plan) for clean cooking in Cameroon (Bruce et al. 2018; GLPGP 2016). This plan includes policy and regulatory enhancements and all necessary investments and interventions along the LPG value chain to achieve this target. The Master Plan was publicly announced by the government in December 2016 (SEforALL 2016).

The main aim of the current study was to quantify the potential health benefits and global climate impact of expanding LPG primary adoption for household cooking in Cameroon, according to the Master Plan targets.

Methods

We applied modeling techniques to synthesize the available evidence and to estimate the potential health and climate impacts of scaling-up the use of LPG as a primary cooking fuel for household use under different policy scenarios in Cameroon. The health and climate impact models were independent but shared common assumptions regarding population demographics and LPG adoption. For the latter, it was assumed that all households made use of LPG as the primary cooking fuel for their daily cooking (implying very limited to no use of traditional biomass fuels; for the climate modeling, this assumption was translated as a complete fuel switch).

We split our analysis into the two consecutive periods: *a*) a short-term (2017–2030) period in line with Cameroonian government targets and *b*) a longer-term (2031–2100) period in line with a default time horizon for most climate projections, making additional policy assumptions to investigate the longer-term impacts on climate. We avoided venturing a health impact projection for the longer-term period because population sociodemographics and disease burden are fast-evolving and highly volatile phenomena that would render any long-term projection highly uncertain.

Population Size and Growth

We used the same midyear population estimates for both health and climate impact modeling. For the years 2011 to 2030, we used the official midyear total population size projections from the National Statistics Institute of Cameroon (Table S1) (INS 2011; GLPGP 2016). Midyear population projection from 2015 onward were reported in 5-y intervals only, and we used linear interpolation to estimate population sizes for the years between the reported years.

For the health impact modeling, we additionally required the number of children under the age of 5 y and the number of households that were not available from the National Statistics Institute of Cameroon. For the former, we used the estimate for the proportion of children under the age of 5 y in 2005, which was approximately 16.6% of the population (INS 2011), and we assumed this proportion remained constant over time. For the latter, we used the mean household size in Cameroon in 2011, which is five (INS and ICF International 2012), and we assumed that this number also remained constant over time.

For the subsequent years after 2030 and up to 2100, we used the United Nations (U.N.) population projections (U.N. DESA 2017) because of the unavailability of official long-term population projections from the National Statistics Institute of Cameroon. To avoid a population size jump in the transition from one projection to the other, we calibrated the UN projections by calculating the ratio between the two projections for the common years (2017–2030). We then projected the ratio assuming logarithmic growth and multiplied it by the median UN population projection. This approach produced a more conservative population projection than the median population projection from the UN, with better alignment to the official population projections from the National Statistics Institute of Cameroon. The population projection we used was well within the 80% uncertainty intervals of the UN estimates.

The Modeling Scenarios

Short-term (ST) — 2017 to 2030 (health and climate). We produced two scenarios for LPG penetration in Cameroonian households for the 2017–2030 period, used for both health and climate impacts modeling (Table 1 and Figure 1).

"Business as usual" scenario (BAU-ST): In this scenario, we assumed that the primary adoption of LPG would increase over time in line with past and current trends (i.e., without implementation of the Master Plan). This increase would lead to an estimated 32% household adoption by 2030, from approximately 25% in 2017, based on 2011 data (INS and ICF International 2012). We calculated these estimates as follows: In 2011, approximately 17.5% of 4 million Cameroonian households were primarily using LPG for cooking, based on nationally representative survey data (Table S1) (INS and ICF International 2012). For the same year, LPG consumption for the household sector (e.g., in cylinders) was estimated at 63,195 metric ton (GLPGP 2016). Consequently, the mean LPG annual consumption per household that primarily used LPG was about 90 kg per household (or 18 kg per capita) in 2011. In our analysis, we assumed that this mean LPG annual consumption per household remained constant over the years; in other words, households that primarily use LPG for cooking will not

Table 1. Overview of policy scenarios that were included in this study. The scenarios differ only in the assumed liquefied petroleum gas (LPG) penetrations. We assessed only the health impact of the scenarios for the short-term period, and we assessed the climate impact for both periods. We estimated an LPG penetration of approximately 25% in 2017.

Period	Scenario	Abbreviation	% of households using LPG by the end year of the relevant period
Short-term (2017–2030)	Business as usual	BAU-ST	32.3
	Master Plan-implementation scenario	MI-ST	57.8
Longer-term (2031–2100)	Business as usual	BAU-LT	40.9
	Post Master Plan-minimum	Min-LT	50.6
	Post Master Plan-saturation	Sat-LT	72.6
	Post Master Plan-maximum	Max-LT	100

Note: "Business as usual" scenarios (BAU-ST) assumes adoption of LPG increases over time in line with past and current trends. Master Plan Implementation scenario (MI-ST) is based on the Cameroon government's aspirational target for household adoption of LPG as a primary fuel to reach 57.8% in 2030.
Post Master Plan—minimum (Min-LT) assumes a return to the pre-Master Plan implementation LPG investment levels after 2030.
Post Master Plan—saturation (Sat-LT) assumes a mature and saturated LPG market is achieved, following the implementation of the Master Plan similar to adoption rates observed in mature LPG markets.
Post Master Plan—maximum (Max-LT) sets LPG adoption at a theoretical maximum of 100%.

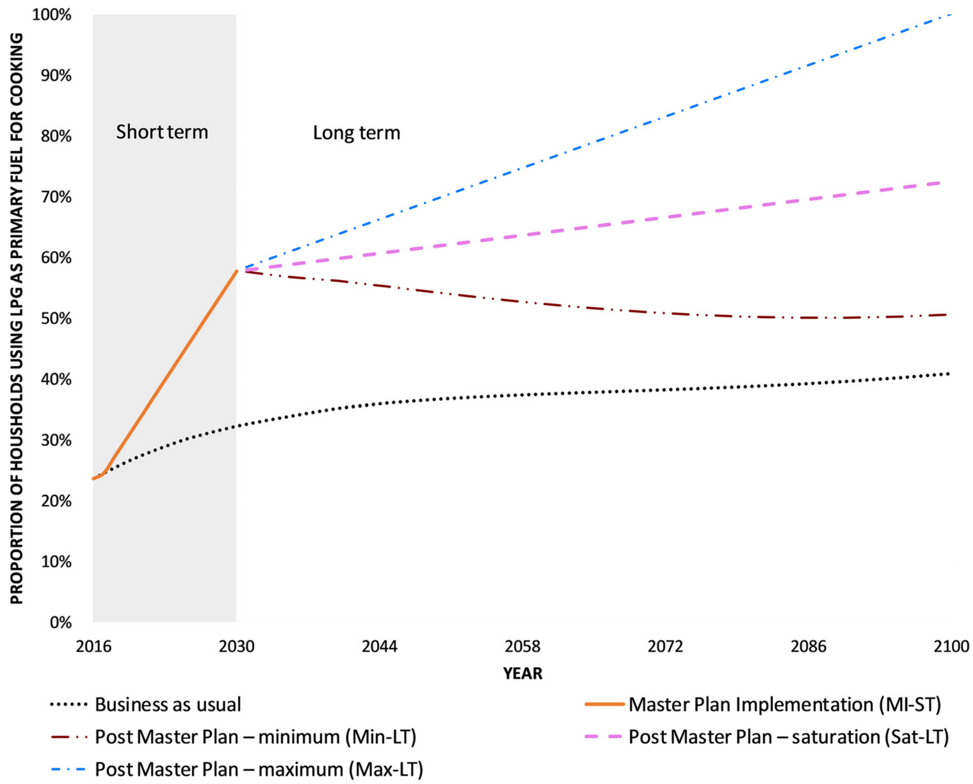

Figure 1. Liquefied Petroleum Gas (LPG) primary adoption of the different modeling scenarios over time. Note: "Business as usual" scenario (BAU-ST) assumes adoption of LPG increases over time in line with past and current trends form approximately 25% in 2017 to approximately 32% in 2030. Master Plan Implementation scenario (MI-ST) is based on the Cameroon government's aspirational target for household adoption of LPG as a primary fuel to reach 58% in 2030 form approximately 25% in 2017. Post Master Plan—minimum (Min-LT): assumes a return to the pre-Master Plan implementation LPG investment levels after 2030. Post Master Plan—saturation (Sat-LT) assumes a mature and saturated LPG market is achieved, following the implementation of the Master Plan similar to adoption rates observed in mature LPG markets. Post Master Plan—maximum (Max-LT) sets LPG primary adoption at a theoretical maximum of 100% (all households cooking primarily with LPG).

change their LPG consumption in comparison with consumption in 2011. Then, we used the projection of LPG cylinder consumption for the years 2015–2030, which is based on historical consumption data from 1995 to 2014, showing consumption is expected to double over this period (GLPGP 2019). We estimated using linear interpolation that this increase corresponds to 66,447 new households adopting LPG as their primary cooking fuel every year. We then used this figure to calculate the proportion of households with primary LPG usage for the years 2017– 2030.

Master plan implementation scenario (MI-ST): This scenario is based on the Cameroon government's aspirational target for household adoption of LPG as a primary fuel to reach 58% in 2030. The higher adoption rate could be made possible by increasing the cylinder investment rate to approximately 400,000 additional cylinders per year (equivalent to 1 cylinder for every 4 persons) and growth in LPG infrastructure and sales outlets (GLPGP 2016, 2019). For this scenario, we assumed that implementation of the Master Plan would start in 2017 after its publication, and household adoption of LPG would gradually increase linearly until 2030 when it reaches the target of 58%.

Longer-term (LT)—2031–2100 (climate). From 2031 to 2100, climate impact modeling is based on four theoretical scenarios, one in line with current trends and three relating to different levels of LPG adoption in Cameroon after implementation of the LPG Master Plan (Table 1 and Figure 1). Because we are not aware of any government plans post-2030 regarding LPG, our scenarios below describe potential alternative futures to map the policy space:

"Business as usual—continuation" scenario (BAU-LT): This scenario is based on LPG adoption increasing in line with past and current trends, if the Master Plan and associated investments were not implemented. Continuing the assumption of the BAU-ST scenario that 66,447 new households every year would adopt LPG as a primary cooking fuel, we estimated that approximately 41% of Cameroonian households could use LPG as primary cooking fuel by the year 2100.

Post–Master Plan—minimum (Min-LT): This scenario is based on returning to the pre-Master Plan implementation investment level after 2030 (i.e., investment of cylinders going back to 66,000 cylinders per year, meaning less availability and access to refills for the end users). For the scenario, we assumed that the increased rate of LPG adoption after 2030 would reduce to the level before the Master Plan implementation (66,447 households per year). This reduction would result in a final LPG adoption figure of approximately 51% of Cameroonian households using LPG as primary cooking fuel by the year 2100. This result is less than 58% (the target for 2030) because the increase rate was modeled on the absolute scale, and its effect is partly counteracted by the projected increase in the population size of Cameroon. Therefore, this scenario represents potential disinvestment in cylinders after the implementation of the Master Plan.

Post Master Plan—saturation (Sat-LT): For this scenario, we assumed that Cameroon, following implementation of the Master Plan, would become a mature and saturated LPG market by the year 2100, achieving levels of LPG adoption as a primary cooking fuel similar to those observed in mature LPG markets, such as those of Latin America (Troncoso and Soares da Silva 2017). In the saturation model, we assumed a final LPG adoption figure of approximately 73% in 2100. We based the target of 73% on the mean proportion of households primarily using LPG or natural gas in Latin America, excluding Haiti as an extreme outlier (Troncoso and Soares da Silva 2017). Given that natural gas penetration rates are relatively low in Latin America and LPG is the predominant gas fuel in most markets, we have ignored them.

Post Master Plan—maximum (Max-LT): The final scenario sets LPG adoption at a theoretical maximum of 100% of the population by 2100 and assumes a gradual linear increase of LPG adoption between 2030 and 2100.

We compared all policy scenarios with the BAU scenario for the respective time frame.

Health Impact Modeling

We modeled the potential health impacts from large-scale LPG adoption as primary cooking fuel via the implementation of the Master Plan in Cameroon from 2017 to 2030 using the HAPIT v3.1 computer model (Pillarisetti et al. 2016; https://householdenergy.shinyapps.io/hapit3/).

HAPIT v3.1 enables estimation of the potential health impacts of HAP using data from the Global Burden of Disease (GBD) 2013. The GBD is an annual risk assessment describing the proportion of deaths that can be attributed to various risk factors (e.g., HAP) and the number of deaths and DALYs attributable to each risk factor (IHME 2018).

GBD assumptions. The GBD has several assumptions that are worth noting. Exposure to HAP is represented by levels of PM less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) because this is the most damaging pollutant and commonly exposure metric used in HAP epidemiological studies. $PM_{2.5}$ is causally associated with several respiratory and circulatory diseases (Shupler et al. 2018a), despite other possible harmful constituents of HAP (e.g., carbon monoxide, black carbon (BC), polycyclic aromatic hydrocarbons). In GBD, mortality and morbidity due to HAP is available for a limited number of diseases for which sufficient evidence exists to support a causal link, namely: respiratory diseases [chronic obstructive pulmonary disease (COPD), lung cancer, acute lower respiratory infections (ALRI) in children under the age of 5 y], and cardiovascular diseases (CVD, ischemic heart disease and stroke).

To estimate DALYs and mortality from levels of $PM_{2.5}$, HAP-$PM_{2.5}$ exposure–response functions are used to link $PM_{2.5}$ concentrations to a relative risk of dying from a causally associated disease. The relative risk is based on what expected deaths and DALYs would be at a counterfactual exposure of 7 $\mu g/m^3$, which represents average ambient levels in the cleanest cities in the world (Smith et al. 2014).

Due to an insufficient number of HAP-$PM_{2.5}$ epidemiological studies for certain diseases (e.g., stroke, ischemic heart disease), "integrated" exposure–response functions also include $PM_{2.5}$ exposures from other sources (e.g., ambient air pollution, secondhand smoke, active smoking). Therefore, the estimates of DALYs and mortality of CVD due to HAP do not account for potential differences in health effects due to the chemical composition of $PM_{2.5}$ from various sources.

HAPIT inputs and assumptions. HAPIT requires both HAP exposure and demographic inputs. Demographic inputs include the total sample size for the intervention, mean household size, and the mean proportion of males, females, and children per household. HAPIT obtains average household size from data housed by the UN Procurement Division and Clean Cooking Alliance's Country Profiles (https://www.cleancookingalliance.org/country-profiles/all.html). All demographics in HAPIT remain constant over time.

HAPIT requires three specific population subgroups [men (noncooks), women (cooks), children under the age of 5 y] because the GBD assesses health impacts differentially according to the subgroup (e.g., HAP-$PM_{2.5}$ exposure–response curves for ALRI apply only to children under the age of 5 y). All women are assumed to be the cooks of the household, regardless of age, and their expected health impacts are expected to be higher because of their increased time spent in the cooking area, relative to males. All 5-y-old or older children are equivalent to noncooking adults. Although this designation may be an oversimplification of age and subgroups for health impact assessment, HAPIT specifies these groups to mimic the comparative risk assessment used in GBD, which offers the most comprehensive global health risk analysis of HAP.

For HAPIT exposure inputs, the mean and standard deviation of HAP-$PM_{2.5}$ exposures for the cooks (women) at "pre- and post-intervention" are needed. For men and children exposures, rather than entering an exposure value into HAPIT, exposure ratios are used [e.g., "other adults (men) to cook exposure ratio" and the "child (under the age of 5 y) to mother exposure ratio"]. Moreover, HAPIT does not allow the setting of these ratios for pre- and postintervention independently. Therefore, HAPIT forces the user to assume that the "other adults (men) to cook exposure ratio" and the "child (under the age of 5 y) to mother exposure ratio" remain constant before and after the intervention (see Appendix 1). Exposure ratios are used in the GBD to assign exposures to men and children because women are typically the most common subgroup monitored in HAP exposure assessments due to their central role as the main cooks (Shupler et al. 2018b). The default "noncook to cook" and "child to cook" exposure ratios of 0.6 and 0.85, respectively, in HAPIT were obtained from an exposure modeling study in India (Balakrishnan et al. 2013).

HAPIT allows only for short-term interventions (up to 5 y) because it assumes that changes in $PM_{2.5}$ exposure happen instantaneously, and it does not allow for population growth and mortality time trends in its calculations (Appendix 1). In the adult mortality calculations, HAPIT uses a 5-y lag structure, where 30% of the total mortality reductions occur in the first year after introduction of the intervention, and 50% is distributed evenly among years 2 through 5. This lag structure is in accordance with the U.S. Environmental Protection Agency recommendation (SAB 2004). However, the remaining 20% is ignored because HAPIT restricts the maximum intervention duration to five years.

Comparative risk approach. HAPIT was used in two separate modeling approaches. The first approach, labeled the "comparative risk" approach, was limited to HAPIT exclusively without any external data manipulations. For Cameroon, we set the mean household size to 5 (INS and ICF International 2012). We set the mean number of children under the age of 5 y per household to 0.8 children per household. This value is the default parameter value for Cameroon in HAPIT and is derived from IHME-modeled estimates of the population under 5 y divided by the number of households in Cameroon (IHME 2018). The value was very close to the reported proportion of children under the age of 5 y in Cameroon for 2005 (INS 2011). We modeled 1 million households (the maximum allowed by HAPIT) and scaled up the results to the Cameroon population (Table S1). We set the intervention time in HAPIT to 5 y, the maximum allowed.

We used data from the LPG Adoption in Cameroon Evaluation (LACE) studies, which were collected over a 48-h period from 102 women and 56 children under the age of 5 y from peri-urban and rural households in Southwest (SW) Cameroon exclusively using wood fuel and 67 women and 60 children from households primarily using LPG fuel (Bruce et al. 2015, Pope et al. 2018a). Households sampled within both peri-urban and rural communities in the LACE studies were selected using stratified random sampling (Pope et al. 2018b).

We assumed that the women's (cooks') and children's exposures documented by the LACE studies are nationally representative of exposures during and after the implementation of the Master Plan. Inherent in this assumption is that the fuel mixture in the new LPG adopters under the Master Plan, and therefore the $PM_{2.5}$ exposure will match that from LACE (where LPG was used as primary cooking fuel but not exclusively) (Appendix 1).

We fit log-normal distributions to pre- and postintervention $PM_{2.5}$ exposure from the LACE studies using maximum likelihood estimation (Venables et al. 2002) for women (cook) and children (<5). We entered the resulting mean and standard deviation (SD) of the log-normal distribution for women into HAPIT (Table S2). If the mean and SD had been calculated directly from the observed LACE data to inform HAPIT, HAP exposure would have been overestimated because the observed data were right-skewed.

For children under the age of 5 y, we calculated (and input into HAPIT) the child-to-cook $PM_{2.5}$ exposure ratio in each LACE household, and then we calculated the mean of this ratio over all households, ignoring the fuel use group (0.82). Our estimate was close to the 0.85 default in HAPIT (Smith et al. 2014) and 0.87 from the Bayesian modeling study (Shupler et al. 2018b) and, in fact, was the most conservative among them. Men's exposure data were not collected in LACE (Appendix 1). Therefore, we used the default of 0.6 in HAPIT.

Dynamic approach. For the dynamic approach, we used the same HAPIT inputs as the comparative risk approach and additional calculations outside the HAPIT model to introduce the dimension of time in the modeling approach. We decomposed HAPIT outputs and extracted the mean number of averted deaths (and DALYs) per new household that primarily uses LPG per year, which is equivalent to the population-attributable fraction. We used this method to estimate the absolute number of averted deaths and DALYs by 2030 that can be attributed to successful implementation of the Master Plan considering: *a*) a gradual adoption of LPG as primary cooking fuel reaching 58% of the population by 2030, *b*) population growth based on population projections (Table S1), and *c*) future disease burden forecasts (Table S3, Figures S1–S10).

We first allowed for the gradual linear adoption of LPG from approximately 25% in 2017 to 58% of the population in 2030. We assumed that the population structure by age and sex remained constant because HAPIT does not produce disaggregated outputs by age group and sex that are necessary to model an evolving population structure (Appendix 1).

By multiplying this number by the mean number of averted deaths per new household with an LPG cookstove per year extracted from HAPIT, we calculated the number of averted deaths by year from 2017 to 2030. To ease the assumption of the constant child to cook ratio pre- and postintervention, we ran HAPIT assuming the household size of 1 with 1 child and 0 adults, and the child exposure from LACE placed in the cook input field (Table S2). Then, we defined child-to-cook ratio = 1. This approach "forced" HAPIT to use the children's exposure measurements from the LACE study and allowed a more accurate estimation of the mean number of averted deaths from ALRI in children under the age of 5 y.

Additionally, in the calculations above for adult mortality, we allowed for a 20-y lag structure, where 30% of the total mortality reductions occur in the first year, 50% is distributed evenly among years 2 through 5, and the remaining 20% is distributed evenly among years 6 through 20, following the U.S. Environmental Protection Agency recommendation (SAB 2004). As we described above, the comparative risk approach follows a similar method for time lags but restricts them to 5 y (Appendix 1).

Projecting health impacts beyond 5 y. To incorporate future disease trends in our estimations, we used the GBD database to extract mortality rate trends from the ARLI in children under age 5 y, and age-standardized mortality rate trends for COPD, lung cancer, ischemic heart disease, and stroke for years 1990–2016 (Table S3, Figures S1–S10) (IHME 2018). Then, for each disease, we fit exponential smoothing models with additive errors, damped additive trends, and no seasonality because these models had the best fit using the Akaike's Information Criterion corrected for small sample bias. We used the exponential smoothing models to project mortality rate trends for the period 2017–2030. We used R v3.6.0 and the R package "forecast" v8.4 to fit and forecast these models (functions "ets" and "forecast") (Hyndman and Khandakar 2008). Then, for each disease, we calculated the rate of increase (or decrease) using 2013 as a baseline. We multiplied this with the previously calculated number of averted deaths by year from 2017 to 2030.

Uncertainty and one-way sensitivity analysis. HAPIT uses the 5th and 95th percentile of the $PM_{2.5}$ relative risk distribution for each health end point to estimate the minimum and maximum averted deaths and DALYs, respectively. We report these estimates when we report results from the comparative risk approach. For the dynamic approach, we ran the same process we describe above, three times: one process using the point estimates from HAPIT with the mean disease burden projections, one using the minimum estimates from HAPIT with the lower 2.5th percentile of the disease burden projections, and one using the maximum estimates from HAPIT with the lower 97.5th percentile of the disease burden projections forecasts. We report these findings as the mean, minimum, and maximum estimates, respectively.

Climate Impact Modeling

To calculate impacts on emissions from combustion of solid fuels and LPG, we used an emission baseline scenario based on the current legislation from the Evaluating the Climate and Air Quality Impacts of Short-lived Pollutants (ECLIPSE) study [European DG Research FP7 project, see; http://www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5a.html (Klimont et al. 2017; Stohl et al. 2015)]. The ECLIPSE emission data were created with the GAINS model (Greenhouse gas–Air pollution Interactions and Synergies; http://www.iiasa.ac.at/web/home/research/researchPrograms/GAINS.en.html), which provides emission of different components in a consistent framework. The GAINS model is based on key sources of emissions, environmental policies, mitigation opportunities, and projections of energy use. We calculated emissions for Cameroon based on the geographical grids (0.5–0.5-degree grid box sizes) within the country boundaries. Baseline emissions data were taken to represent the domestic sector (cooking with biomass, not coal, and excluding lighting and heating). The emissions growth was projected assuming a linear trend between 2017 and 2050, where 2050 is the final year in the ECLIPSE emission data set. The ECLIPSE data set provided the baseline (current) emissions of all the components investigated except CO_2 (Appendix 2). As we studied only emission differences between scenarios, we estimated the change in emission of CO_2 based on ratios between BC and carbon dioxide (CO_2) when replacing fuelwood with LPG (Grieshop et al. 2011). We next estimated the amount of fuel use at baseline together with assumed fractions of nonrenewable harvesting of biomass. Most of the wood goes directly to fuelwood, but a fraction is used for charcoal produced and consumed in Cameroon. Bailis et al. estimated that fuelwood and charcoal constituted 97% and 3% of the total biomass combustion in 2009 in Cameroon, respectively (Bailis et al. 2015). We have assumed that these proportions remain constant over time (Appendix 2).

In general, the combustion of cooking fuels leads to a range of emissions (Table S4). Aerosols and ozone precursors perturb the atmosphere on short time scales (weeks to a few years), whereas greenhouse gases such as CO_2 influence the atmospheric composition on longer time scales (years to hundreds of years) (IPCC 2014). BC is the main heating component from renewable biomass fuel, and CO_2 is the main heating component from LPG (Grieshop et al. 2011). Other components, such as organic carbon (OC) and sulfur dioxide (SO_2), cool the climate. Our emission estimates are based on several studies on emission factors and stove efficiencies given different combinations of stoves and fuels (Grieshop et al. 2011; Sparrevik et al. 2015; Zhang et al. 2000). These studies consist of either measurements in the field or measurements in the lab. The Grieshop et al. (2011) study combines measurements from a range of other studies. We have selected the stove-fuel combination we find the most representative for Cameroon. For fuelwood, we have used emission factors for traditional stove, burning wood unvented (i.e., stove without chimney); for LPG, an LPG metal stove unvented; and for charcoal, a charcoal stove unvented, all from Grieshop et al. (2011) for all species except NO_x. We supplemented nitrogen oxide (NO_x) emission factors with values from Zhang et al. (2000) with a metal stove without flue from India with brushwood, fuelwood for fuelwood and charcoal, and LPG traditional stove without a flue for LPG. Because charcoal is produced locally, we also included emissions from production. We applied emissions factors that are the average of Sparrevik et al. (2015). For BC, OC, and SO_2, the emission factors were scaled based on emissions of CO, methane (CH_4), and volatile organic compounds (VOC) due to lack of separate emission factors. Emissions of BC are reduced significantly when replacing solid fuels with LPG; they are reduced by a factor of 10 per unit fuel.

The emission factor of CO_2 for fuelwood depends on the amount of nonrenewable biomass. The higher the fraction of nonrenewable (fNRB), the higher the emission factors. The anthropogenic CO_2 emissions of fuelwood are estimated as a fraction of the CO_2 released from burning wood, where only the nonrenewable material is included:

$$\Delta E_{CO_2} = f_{NRB} \times \Delta E_{CO_2,fuelwood}.$$

Estimates from the literature reveal extensive uncertainties when it comes to the fraction of nonrenewable biomass (fNRB) in Cameroon. This uncertainty is also the case in many other countries and regions (Bailis et al. 2017). In a spatially explicit assessment of pantropical fuelwood supply and demand, Bailis et al. (2015) found that the fNRB related to wood that was directly harvested as fuel was lower than 10% in Cameroon. However, how much of this deforestation is driven by domestic cooking is uncertain. This estimate did not account for the fuelwood that was a by-product of various land cover changing processes not primarily related to fuel production. In a recent study on carbon-offsets projects, Bailis et al. (2017) estimated the fNRB in a range of projects in African regions, including one gold-standard project in Cameroon. For that project, the authors were not able to assess the fNRB, which was estimated at 0%–100%. In comparison with other countries, the estimated range of fNRB varied considerably in other West and Central African countries, but in most cases, the upper estimate was below 30%. Exceptions were Nigeria and Burkina Faso, where the upper estimate was ∼50%. In the Central African countries included in the study, the fNRB was generally below 20%. In our calculations, we use a best average estimate of 10% for Cameroon based on the upper value reported in Bailis et al. (2015) and give an uncertainty range of 0%–50% based on Bailis et al. (2017).

We estimated the climate impacts of the planned LPG expansion in two different ways. The first way was to estimate the CO_2-equivalent emissions of the estimated MI-ST vs. BAU-ST in 2030 with various emission metrics. The second was to estimate the global temperature perturbation until 2100 for the Master Plan scenarios vs. BAU.

Emission metrics were developed at the time of the first assessment report from the IPCC. Comprehensive climate policy will require a simple method of evaluating the climate impact of emissions of different species. Emission metrics are tools that provide an exchange rate between different species. The emission metrics applied in this study are the Global Warming Potential (GWP) (IPCC 1990) and Global Temperature change Potential (GTP) (Shine et al. 2005) as given in Aamaas et al. (2013). Metric values that were used and references are shown in Table S5. GWP (100) is the most common and used in official emission statistics, whereas GTP is more relevant in the context of limiting the global temperature increase. Both GWP and GTP are useful as GWP reflects radiative forcing directly connected to changes in atmospheric concentrations, whereas the global temperature is further down the cause–effect chain, but with increased uncertainty. We have mostly applied the same emission metric parameterizations as those used in the Fifth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC 2014). However, we increased the metric values of CH_4 by 14% because newer research has shown larger radiative forcing from CH_4 due to processes previously not accounted for (Etminan et al. 2016).

GWP for component i at time H is

$$GWP_i(H) = \frac{AGWP_i(H)}{AGWP_{CO_2}(H)} = \frac{\int_0^H RF_i(t)dt}{\int_0^H RF_{CO_2}(t)dt},$$

where the accumulated radiative forcing (RF) for the component is normalized to the accumulated RF for CO_2 in the same period. GWP is a relative measure of how much heat a greenhouse gas traps in the atmosphere when compared with a similar mass of CO_2 over a specific time interval. GTP for component i at time H is

$$GTP_i(H) = \frac{AGTP_i(H)}{AGTP_{CO_2}(H)} = \frac{\int_0^H RF_i(t)dt\, IRF_T(H-t)dt}{\int_0^H RF_{CO_2}(t)dt\, IRF_T(H-t)dt},$$

where IRF_T is a simple parameterization for the temperature response given an instantaneous RF; AGTP gives the temporal global temperature response of a pulse emission of a component.

By applying these emission metrics, all emission perturbations can be converted into CO_2-equivalent emissions:

$$CO_2eq(H) = M_i(H) \times \Delta E_{i,s},$$

where M is metric GWP or GTP, and ΔE is the emission perturbation in scenarios, and in our case, the emission difference between BAU-ST and MI-ST in 2030.

AGTP can also be used to calculate temporal global temperature responses, as AGTP can be seen as a very simple climate model. We have therefore estimated the temperature response of different emission scenarios vs. BAU using this convolution:

$$\Delta T_{s,i}(H) = \int_0^H \Delta E_{s,i}(t) \times AGTP_i(H-t)dt,$$

where, ΔT is the total temperature impact for component i at time H following policy scenario s relative to BAU with the emission perturbation ΔE at time t relative to baseline.

Table 2. Estimated averted deaths and disability-adjusted life years (DALYs) from the modeled increase of liquefied petroleum gas (LPG) penetration to 58% in 2030 from 25% in 2017 [Master Plan scenario (MI-ST)].

	Comparative risk approach		Dynamic approach	
Disease	Averted deaths [min, max (thousands)]	Averted DALYs [min, max (thousands)]	Averted deaths [min, max (thousands)]	Averted DALYs [min, max (thousands)]
Acute lower respiratory infection (age <5 y old)	3.8 (2.7, 4.5)	330 (230, 390)	2.0 (1.3, 3.2)	170 (110, 270)
Chronic obstructive pulmonary disease	1.0 (0.62, 1.4)	40 (24, 52)	1.4 (1.1, 1.9)	56 (45, 69)
Ischemic heart disease	4.2 (3.2, 6.9)	94 (71, 160)	5.7 (4.3, 7.7)	120 (83, 180)
Lung cancer	0.23 (0.1, 0.29)	5.7 (2.6, 7.1)	0.35 (0.29, 0.41)	15 (13, 16)
Stroke	14 (4.7, 17)	290 (100, 360)	19 (16, 22)	400 (330, 490)
Total	23 (11, 30)	760 (430, 960)	28 (22, 35)	770 (580, 1,000)

Note: We modeled health impacts from large-scale LPG adoption via the implementation of the Master Plan in Cameroon from 2017 to 2030 using the HAPIT v3.1 computer model (Pillarisetti et al. 2016). We used HAPIT exclusively for the comparative risk approach, whereas for the dynamic approach, we postprocessed HAPIT outputs in a novel approach to ease some of its assumptions and introduce the dimension of time. Results are rounded to the second significant digit and presented in thousands. The counterfactual scenario assumed an increase of LPG penetration to 32% in 2030 [Business as Usual scenario (BAU-ST)].

The emission metric methodology assumes linearity in the temperature responses and that the impact of each emission component can be added together. Appendix 2 summarizes the key modeling assumptions and limitations for the climate impact modeling.

Results

Short-Term (2017–2030)

Health impacts. Using the "comparative risk approach," we estimated that approximately 23,000 (minimum = 11,000, maximum = 30,000) deaths and 760,000 (minimum = 430,000, maximum = 960,000) DALYs could be averted within 5 y of the Master Plan implementation (scenario: MI-ST). This reduction represents about 36% of all HAP-related deaths in Cameroon and about 35% of all HAP-related DALYs (calculated over 5 y). With the more detailed "dynamic approach," we estimated that the implementation of the Master Plan might avert approximately 28,000 (minimum = 22,000, maximum = 35,000) deaths and 770,000 (minimum = 580,000, maximum = 1 million) DALYs between 2017 and 2030. These estimates represent approximately 19% of all HAP-related deaths and 15% of all HAP-related DALYs (Table 2) (calculated over 13 y, resulting in a larger denominator and therefore lower percentages). Reassuringly, the estimates of averted deaths from both approaches are comparable, despite the different assumptions. Estimates from the comparative risk approach are approximately 20% lower than those from dynamic approach that could be, at least partly, explained by the 5-y limited lag structure of HAPIT (please refer to relevant paragraph in the "Methods" section). It is interesting to note that the averted ALRI deaths estimates are substantially less in the dynamic approach, unlike estimates for other HAP-related diseases. This difference can be explained because the dynamic approach incorporates disease trends in its projections, and the ALRI burden in children under 5 years of age in Cameroon has declined quickly over recent years (Table S3, Figure S1).

Climate impacts. Biomass-burning cookstoves are a substantial source of emissions in Cameroon, contributing about 60% of the national emissions of BC, according to the ECLIPSE emission data set. Under the BAU-ST scenario, estimated emissions of all species increased by ∼10%–20% from 2017 to 2030 (Table 3). The estimated relative emission growth under the BAU-ST scenario was somewhat smaller than the relative population growth. This difference may be due to the uptake of LPG and other clean fuels, as well as efficiency improvements.

Under the MI-ST scenario, we estimated a total net reduction in emissions in 2030 of ∼38% for most emissions components (BC: −37%, OC: −38%, SO_2: −38%, NO_x: −37%, CO: −37%, VOC: −26%, CH_4: −38%) (Table S5). The emissions that can potentially be added due to increased usage of LPG fuel are substantially less than the potential reduction in emissions due to reduced use of biomass fuel for cookstoves. This difference can be explained by the lower emission factors for LPG fuel (Table S4) and much higher LPG stove efficiencies.

Converting the emission difference between MI-ST and BAU-ST in 2030 into CO_2-equivalents, our estimates suggest a cooling effect of GWP with a time horizon of 100 years (GWP_{100}) equal to −4.5 Mt CO_2-equivalent (Table 4). The estimated climate benefit of fuel-switching to LPG is greater the larger that the percentage of nonrenewable biomass (fNRB) is. For a 50% nonrenewable biomass, our upper uncertainty range level for the fNRB, the estimated cooling effect of the LPG Master Plan equaled emissions of −7.6 Mt CO_2-equivalent. It is interesting to note that we estimated that if biomass used for fuel has an fNRB of more than 61%, the CO_2 emission increase from burning LPG is counteracted by the reduction in CO_2 emissions from reductions in deforestation. Thus, an fNRB of 61% is the break-even level for the CO_2 effect in our calculations for Cameroon.

We estimated that the cooling effect of MI-ST vs. BAU-ST in 2030 was larger with a shorter time horizon, increasing to −18 Mt CO_2-equivalent when applying GWP (20), i.e., with a time horizon

Table 3. Estimated emissions from biomass and LPG cookstoves in Cameroon in 2017 and 2030 under "Business as usual" (BAU) and Master Plan–implementation (MI-ST) assumptions, respectively.

Emissions (Mt[a])	BC	OC	SO_2	NO_x	CO	VOC	CH_4	CO_2
2017	0.017	0.042	0.0066	0.0037	1.1	0.11	0.061	N/A
2030, BAU-ST	0.019	0.050	0.0080	0.0044	1.3	0.13	0.072	N/A
2030, MI-ST	0.012	0.031	0.0050	0.0028	0.85	0.12	0.045	0.84[b]
2030, reduction in MI-ST relative to BAU-ST	−37%	−38%	−38%	−37%	−37%	−26%	−38%	N/A

[a]Million tons.
[b]Total emissions of CO_2 include a reduction in deforestation due to reduced demand for nonrenewable biomass. Because the ECLIPSE data set does not provide CO_2 emissions from the domestic sector, the value shows the emission difference. A relative change can therefore not be calculated for CO_2.

Table 4. Emission difference between "Master Plan–implementation" scenario (MI-ST) and "Business as Usual" scenario (BAU-ST) in Mt CO_2-equivalent in 2030 with various emission metrics.

Component	Emission difference between MI-ST and BAU-ST in 2030 in Mt CO_2-eqv			
Emission metric	GTP(20)	GTP(100)	GWP(20)	GWP(100)
BC	−5.0	−0.65	−17	−4.7
OC	1.3	0.17	4.6	1.3
SO_2	0.12	0.016	0.42	0.12
NO_x	0.37	0.0085	−0.20	0.018
CO	−1.8	−0.13	−2.9	−0.92
VOC	−0.24	−0.020	−0.47	−0.14
CH_4	−2.1	−0.13	−2.6	−0.88
CO_2	0.84	0.84	0.84	0.84
Sum	−6.5	0.10	−18	−4.5

Note: The emissions difference in 2030 between the Master Plan–implementation scenario (MI-ST) and Business as Usual (BAU-ST) have been converted into CO_2-equivalents using alternative emission metrics, Global Warming Potential (GWP) and Global Temperature change Potential (GTP), and time horizons, i.e., 20 and 100 years. GWP (100) is the most common emission metric. These emission differences are based on nonrenewable fraction for biomass of 10%; eqv, equivalent.

of 20 y (Table 4). In general, using emission metrics with a short time horizon gave greater weight to the short-lived climate forcers (including BC and CH_4), implying that reduced emissions of such components will have greater impacts. Applying the metric GTP (100) for MI-ST vs. BAU-ST in 2030 resulted in a slight estimated net increase in CO_2-equivalent emissions from the Master Plan because the estimated warming from increased CO_2 emission from LPG was larger than the estimated cooling from reduced BC emissions (Table 4).

Concerning the effect on temperatures, climate modeling showed an estimated net cooling between 2017 and 2030, dominated by cooling from reduced emissions of BC (Figure 2). The LPG MI-ST scenario may result in an estimated global cooling effect of −0.10 milli °C in 2030. The cooling from reduced BC might potentially be partly counteracted by warming of averted emissions of OC. CO_2 has minor importance in such short time scales.

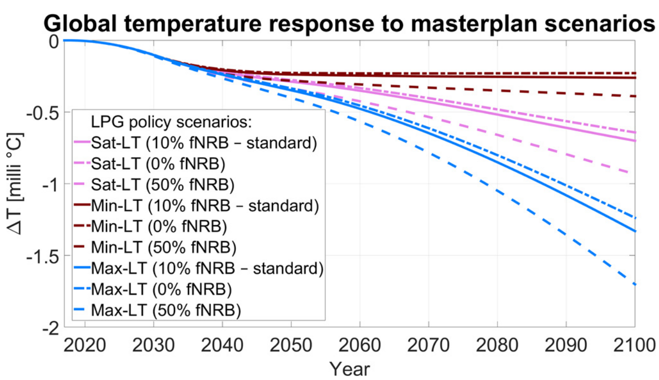

Figure 2. The net global temperature change in the different LPG policy scenarios relative to "Business as Usual" (BAU) until 2100. Note: All the scenarios are the same until 2030 because they follow the Master Plan; however, they separate after 2030 based on different LPG uptake rates. In SAT-LT, we assume Cameroon will be a mature and saturated LPG market in 2100. In Min-LT, the adoption of LPG returns to the pre-Master Plan implementation levels after 2030. The final scenario (Max-LT) is seen as a "maximum," with LPG adoption reaching 100% in 2100. These scenarios are made with different levels of nonrenewable fraction for biomass (fNRB) for the fuelwood. The standard case is fNRB 10%; however, we also have a minimum and a maximum of 0% and 50%. The change in global temperature is estimated on emission scenarios combined with AGTP as a simple climate model. The scenarios deviate after 2030 due to different uptake rates of LPG. Please also refer to the values presented in Table 5.

Longer-Term (2031– 2100)

For the longer-term climate modeling, under the Post Master Plan—minimum (Min-LT) scenario (51% adoption in 2100) relative to the baseline (BAU-LT), the net cooling was estimated at −0.26 milli °C with an fNRB of 10% (see Figure 2 and Table 5). We estimated a larger cooling impact for the Post-Master Plan—saturation (Sat-LT) scenario (73% adoption in 2100), potentially reaching −0.70 milli °C. Finally, we estimated a net cooling of −1.33 milli °C for the Post-Master Plan—maximum (Max-LT) scenario (100% adoption).

The most important contributor to the estimated cooling was through averted BC emissions. However, as mentioned, increased LPG use leads to increased CO_2 emissions. Emissions of CO_2 accumulate in the atmosphere and have an impact for centuries; therefore, the warming effect of CO_2 increases with time, giving the largest offset in the long-term (several decades after 2030). The temperature response of altering BC emissions occurs much faster due to the much shorter atmospheric lifetime (less than 1 wk) of BC. The estimated reductions of CH_4 and CO add to the cooling, whereas the estimated reduced OC emissions could partly counteract the cooling effect of reduced BC, CH_4, and CO. We estimated that the other components had only marginal contributions to the net temperature change.

The results were sensitive to the estimated fNRB of the fuelwood used for cooking (Figure 2). The estimated reduction in global temperature under the Sat-LT scenario in 2100 could be −0.64 milli °C, assuming 100% renewable biomass, but this estimate increased to −0.93 milli °C with only 50% renewable biomass. Figure 2 and Table 5 depict the net global temperature change in the different LPG policy scenarios.

Discussion

Our estimates comparing the proposed implementation of the LPG Master Plan to the current rate of LPG adoption suggest that converting 58% of the population of Cameroon to LPG for household cooking fuel by 2030 would have a substantial positive impact on population mortality and morbidity and on climate. However, the estimated climate impact is highly dependent on the time perspective. In the very long run, the warming effect of added CO_2 emissions is most important, as is seen when applying GTP(100) for pulse emissions. However, in any scenario for this century, the cooling effects of LPG adoption supersede the warming effects. The estimated avoided health damage is considerably greater under the MI-ST scenario than would be the case given the current rate of LPG primary adoption (unassisted by the implementation of the Master Plan and associated investments). Furthermore, switching from biomass to LPG for cooking (assuming exclusive use) in line with the Master Plan target has

Table 5. The net global temperature change in 2030, 2050, and 2100 in different liquefied petroleum gas (LPG) policy scenarios relative to baseline (BAU) with 0%, 10% (standard), 50% nonrenewable fraction for biomass (fNRB).

Scenario	fNRB	Global temperature change (°C)		
		2030	2050	2070
Sat vs. BAU	0%	−0.10	−0.28	−0.64
Sat vs. BAU	10% standard	−0.10	−0.29	−0.7
Sat vs. BAU	50%	−0.11	−0.34	−0.93
Min vs. BAU	0%	−0.10	−0.23	−0.23
Min vs. BAU	10% standard	−0.10	−0.24	−0.26
Min vs. BAU	50%	−0.11	−0.28	−0.39
Max vs. BAU	0%	−0.10	−0.34	−1.2
Max vs. BAU	10% standard	−0.10	−0.35	−1.3
Max vs. BAU	50%	−0.11	−0.4	−1.7

Note: The results presented in this table are also shown in Figure 2.

demonstrable positive impacts on emissions affecting climate and the estimated global temperature response.

To our knowledge, this study is the first one to assess the projected health and climate impacts of scaling the primary adoption of LPG as a clean cooking fuel to national policy target levels in a sub-Saharan Africa country. For example, Permadi et al. (2017) looked at the climate impacts of the kerosene to LPG mega-conversion program impacts in Indonesia (Thoday et al. 2018) and estimated 31% emissions reductions from reduced kerosene use (expressed in CO_2 equivalent) over 3 y from program implementation (although the overall emissions reductions were less, given the continued use of solid fuel cooking that was not targeted by the conversion program); Peng et al. 2017 modeled sectorial mitigations strategies in China (including replacement of 20% of coal-based stoves with LPG). Singh et al. 2017 retrospectively estimated the climate impacts from increased LPG uptake from nationally representative surveys over 10 y (2001–2011) in India. The study calculated approximately 7.2 million tons of national fuelwood displacement from increased LPG adoption (primary and secondary use) associated with a net emissions reduction of 6.73 Mt CO_2-equivalent, assuming 0.3 as fNRB. Besides, other studies in the literature have done similar scenario-based analyses of health (e.g., Steenland et al. 2018) and climate emissions impacts of household cooking fuel transitions, but not primarily focusing on LPG. Anenberg et al. (2017) performed a similar study on clean cookstove programs in Mozambique with four illustrative and schematic scenarios, including one on LPG adoption in urban areas. Pachauri et al. 2018 modeled clean cooking energy transitions in Honduras, Guatemala, and Nicaragua (with different fuel and stove combinations, including LPG); other studies targeted multicountry and multisolutions modeling (e.g., Lacey et al. 2017, Jeuland et al. 2018), with one study looking specifically at sub-Saharan Africa (Dagnachew et al. 2020).

The study by Rosenthal et al. (2018) modeled estimates of the potential health and climate gains for a diverse group of 40 LMICs. The modeling was based on an intervention scenario of 25,000 homes replacing solid fuel with cleaner options, including *a*) a locally made, improved biomass cookstove (ICS), *b*) an advanced biomass combustion (fan) stove (ACS), and *c*) an LPG stove over 3 y with 60% adoption. The authors estimated that implementation of a 25,000-household LPG cookstove program would lead to a fourfold reduction in DALYs and more than 100,000 tons of CO_2-equivalent than one using a basic ICS, concluding that LPG cookstove programs yield greater reductions in both DALYs and Global Warming Commitment in the countries than those using ICS. Even in comparison with ACS, where performance often depends on fuel moisture content, and user operations, the transition to LPG would provide better benefits on both health and climate (Rosenthal et al. 2018).

Our health estimates are likely to slightly underestimate the true impact of sustained LPG adoption if households were to use LPG exclusively for all their cooking tasks. First, in the sample we used to measure exposure to HAP and to inform our health modeling, we found that in some households, exposure was higher than the WHO Indoor Air Quality Guideline ($10\ \mu g/m^3$) but still below the WHO Interim Target 1 (IT-1, $35\ \mu g/m^3$), indicating the likely mixed use of LPG and biomass or a community effect (pollution coming from neighboring households cooking with biomass). Second, HAP from solid fuel use is associated with a variety of other health issues, including cataracts in adult women, adverse pregnancy outcomes, tuberculosis, and laryngeal cancer (Bruce and Smith 2014), which are not currently part of the burden of disease estimation for HAP and therefore were not part of the impact modeling. Third, global warming is expected to increase the disease burden globally (Gasparrini et al. 2017). Therefore, because the implementation of the Master Plan in Cameroon can potentially reduce global warming, it may reduce disease burden globally, which we have not considered in our modeling.

Additionally, substantial benefits related to reduced ambient air pollution will likely occur from the reduction in the contributions of HAP to ambient air pollution. For instance, the contribution from residential solid fuels in China has been estimated to be in the range of 20%–40% of the population-weighted exposure to $PM_{2.5}$ (Aunan et al. 2018). Similar and even higher estimates are found for India (Chowdhury et al. 2019).

Strengths and Limitations

Our scenarios map the short- and longer-term policy space of LPG adoption for cooking in Cameroon and are based on real HAP exposure and GBD disease burden data from Cameroon with analyses of impacts for a publicly endorsed national LPG Master Plan. Our modeling is based on $PM_{2.5}$ personal exposure data collected in the field for women (main cooks) and children from households using traditional biomass stoves (e.g., three-stone, open-fire, and sawdust stoves) and LPG stoves, and projections regarding population size, disease burden, and emissions to quantify the health and climate impact of policy scenarios. The climate modeling is based on a simple but robust methodology, easily replicable for other countries and at a low cost. Moreover, we expanded the functionality of HAPIT to include the dimension of time and achieve more realistic modeling of the Master Plan.

However, relevant information and data in LMICs are lacking, and this aspect was reflected in our modeling strategy, assumptions, and scenarios. It is important to note that in the health impact modeling, we are assuming uniform LPG primary adoption across all urban, peri-urban, and rural areas, which have different demographics and disease burden in Cameroon (Appendix 1). These differences did not account for the differential potential for LPG adoption according to different settings and socio-economic groups (Puzzolo et al. 2016; Shupler et al. 2019). We acknowledge that affordability to the household, prices of competing fuels, supply-chain reliability, and last-mile distribution are all potential factors that contribute to clean fuel adoption, even in best-case scenarios of plentiful cylinder refills available in the market (Rosenthal et al. 2017; Puzzolo et al. 2019). We provide no estimates regarding the health equity of the policy scenarios.

Although HAP exposures in Southwest Cameroon may not be nationally representative (because Southwest Cameroon is an Anglophone region in a majority Francophone country), the LACE studies are one of a few HAP studies collected in both peri-urban and rural environments and therefore represent some of the most comprehensive HAP exposure data conducted in Cameroon to date. A comparison of the average relative difference in female exposures to wood and LPG primary users from LACE ($90\ \mu g/m^3$) to rural areas in Cameroon estimated from a global Bayesian modeling study ($116\ \mu g/m^3$) (Shupler et al. 2018b) showed relatively high agreement, with the measurement from LACE being conservative (possibly because LACE includes peri-urban and rural communities).

Regarding fuel stacking, our model assumes that 58% of the population will primarily rely on LPG (i.e., will use LPG for daily cooking with limited use of polluting traditional fuels), but there is likely to be a gradient of adoption or stacking across different socioeconomic groups (e.g., with poorer households adopting less LPG). Although we acknowledge that a complete fuel switch is unlikely (i.e., a portion of the households will continue to fuel stack), we also expect that the number of stackers may reduce over time due to rapid urbanization rates in Cameroon (with consequent reduced availability to purchase biomass fuels as well as more people in the labor market), and that fuel stacking may be limited to special events and festivities when there is need to cooking for greater numbers of people. In addition, in this study, we have not modeled the concomitant increase of secondary LPG users that also would affect climate modeling because less biomass would be used for cooking, contributing to forest protection. Last, we have also assumed that the share of charcoal of 3% for biomass consumption stays constant because the government is concerned about deforestation, but this share might increase because charcoal is easier to transport and to use than fuelwood in urban settings.

Because there can be large country-level variation in relative differences between men's and women's exposures due to cultural factors such as division of household labor and gender relations (El Tayeb Muneer and Mukhtar Mohamed 2003), assuming the same exposure ratio in Cameroon as that in India may misclassify men's exposures in Cameroon. Furthermore, by not allowing for separate pre- and postintervention exposure ratios, HAPIT does not allow for differences in exposure ratios between households using different cooking fuel types, which may also vary (Shupler et al. 2018b). However, the global Bayesian modeling study estimated region-specific exposure ratios and reported a mean "other to cook" exposure ratio of 0.72, in comparison with 0.6 as we have used, among households using traditional wood in western Africa (Shupler et al. 2018b). Hence, as with children under the age of 5 y, for men's exposure, we used estimates that yield more conservative outputs from HAPIT.

In our climate modeling, we have treated Cameroon as one region, whereas further research could investigate smaller regions and, for instance, be based on different nonrenewable fractions for biomass for different regions. The emission of the studied components will also affect climate parameters other than global temperature, such as precipitation. However, the relevant literature is sparse and somewhat contradictory with large bounds of uncertainty. Finally, the climate modeling should ideally rely on complex earth system models, but such modeling is computationally expensive and complex, impractical for small emissions such as those from Cameroon, and does not provide the flexibility to compare multiple measures and components easily.

Conclusions

Timely implementation of the National LPG Master Plan for Clean Cooking in Cameroon could have substantial population health benefits as well as favorable climate impacts contributing to a reduction in global warming, of which the magnitude is dependent on the time perspective. LPG, differently from other fossils fuels, has the potential to protect the environment as well as to offer substantial health and societal benefits. Further research is needed to explore how to best support national policy and achieve effective implementation of the LPG Master Plan to ensure long-term sustainability and favor equitable adoption of LPG at scale.

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Appendices

Appendix 1. Key assumptions and limitations concerning health impact modeling.

Comparative risk approach
- No population growth (constant age/sex structure of the population), constant disease burden over time.
- HAP health impacts are determined only by levels of $PM_{2.5}$ (an assumption by the GBD study).
- HAPIT v3.1[a] includes only health outcomes assessed in the GBD (2013) study: chronic obstructive pulmonary disease, lung cancer, acute lower respiratory infections (in children <5 y), ischemic heart disease, and stroke.
- For CVD, the health impacts of $PM_{2.5}$ exposures are estimated using other sources (ambient air pollution, secondhand smoke, active smoking). We assume chemical composition of $PM_{2.5}$ from various sources do not affect CVD health impacts.
- HAPIT requires the intervention to be instantaneous, and the maximum useful time of intervention is 5 y. Because of the lag structure, 20% of the intervention effectiveness is ignored.
- $PM_{2.5}$ exposures measured in the LACE[b] studies are nationally representative of exposure in fuel wood exclusive and primarily LPG households.
- Child exposure (age <5 y) is 82% of women's (cooks') exposure in LACE studies.
- Men's exposure is 60% of women (cook) exposure.
- Fuel mixture in households that primarily use LPG in the population will remain constant and similar to that occurred in LACE studies (i.e., not fully exclusive use).
- Uniform LPG primary adoption, demographics, disease burden across all urban, peri-urban, and rural areas in Cameroon.

Dynamic approach
- Shares the same assumptions with the comparative risk approach EXCEPT
- Child exposure (age <5 y) is directly informed from the LACE studies for both fuelwood exclusive and primarily LPG households.
- We allowed population growth and used disease burden projections.

Note: CVD, cardiovascular disease; GBD, global burden of disease; HAP, household air pollution; LPG, liquefied petroleum gas.
[a]HAPIT v3.1 enables estimation of the health impacts that result from HAP interventions that reduce $PM_{2.5}$ exposures, using epidemiological data from the Global Burden of Disease (GBD) 2013 (Pillarisetti et al. 2016; https://householdenergy.shinyapps.io/hapit3/).
[b]The LPG Adoption in Cameroon Evaluation (LACE) studies included 48-hr monitoring of 102 women, 56 children (<5 years of age) from peri-urban and rural households in Southwest Cameroon exclusively using fuelwood and 67 women and 60 children primarily using LPG fuel (Pope et al. 2018b).

Appendix 2. Key assumptions and limitations concerning climate impact modeling.

Climate modeling assumptions
- Current emissions and until 2050 based on the domestic sector given in the ECLIPSE emission dataset (Stohl et al. 2015).
- Emission growth after 2050 would follow population growth.
- Fuelwood to charcoal ratio remained constant over time (i.e., fuelwood and charcoal constituted 97% and 3%, respectively, of total biomass combustion in 2009) (Bailis et al. 2015).
- Emission factors from the literature are representative of stove emissions in Cameroon. Values are given in Table S3 (Grieshop et al. 2011; Sparrevik et al. 2015; Zhang et al. 2000).
- Fraction of nonrenewable biomass harvesting in Cameroon at 10% (Bailis et al. 2015).
- Primary LPG adoption translated as a complete fuel switch.
- Temperature calculations simplified by applying the emission metric AGTP with metric values mostly in line with IPCC (IPCC, 2014; Etminan et al. 2016) (Table S5).
- We assumed the impact of each emission component on global temperature can be added linearly together.

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